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Future challenges and innovations in entomology research

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Abstract

Entomology, the scientific study of insects, stands at one of the most consequential crossroads in its history. On one side lies an accelerating ecological crisis—insect populations are declining at rates that threaten to destabilize ecosystems and agricultural systems worldwide. On the other side stands a technological revolution of extraordinary scope, offering tools of genomic, computational, and biotechnological precision that were unimaginable only two decades ago. This review provides a comprehensive, expanded synthesis of current knowledge and forward projections across nine critical domains: the effects of climate change on insect biology and distribution; the global biodiversity crisis and conservation imperatives; advances and challenges in integrated pest management; the emerging landscape of insect genomics and biotechnology; the role of digital technologies and computational methods; the rise of the insect-based bioeconomy; the evolving challenge of vector-borne disease management; the ethical and governance dimensions of new technologies; and future research priorities. With insects comprising more than 80% of all described animal species and underpinning ecosystem services valued in the hundreds of billions of dollars annually—from pollination and nutrient cycling to biological pest control and decomposition—their ongoing decline poses one of the gravest threats to biodiversity, food security, and human well-being. Simultaneously, breakthrough innovations including CRISPR-Cas9 gene editing, artificial intelligence-assisted species identification, environmental DNA metabarcoding, satellite remote sensing, and population-suppression gene drives are equipping researchers with unprecedented capabilities. This paper argues that the future of entomology will be determined by the scientific community's capacity to integrate these powerful tools with ecological wisdom, inclusive governance, equitable access, and sustained long-term investment in foundational science. The synthesis presented here is intended to inform researchers, policymakers, conservation practitioners, and industry stakeholders about the field's most pressing priorities and most promising opportunities.

Keywords: Entomology, insect decline, climate change, CRISPR gene drives, integrated pest management, insect genomics, bioeconomy, pollinator conservation, vector-borne disease, environmental DNA, biodiversity monitoring, precision agriculture

1. Introduction

Insects constitute the most species-rich and ecologically diverse class of animals on Earth. With approximately one million described species and conservative estimates suggesting four to eight million await formal description, they represent a remarkable evolutionary success story spanning over 400 million years (Stork, 2018) [44]. From the first winged insects of the Carboniferous to the hyperdiverse radiations of beetles, flies, wasps, and butterflies that dominate modern terrestrial ecosystems, insects have co-evolved intimately with plants, fungi, vertebrates, and microorganisms, generating webs of ecological interdependence that underpin much of life on land.

The ecological services provided by insects are both diverse and economically vast. Pollination by bees, hoverflies, moths, and butterflies is estimated to contribute between US\$235 and \$577 billion annually to global food production (IPBES, 2016) [26]. Decomposition by beetles, flies, and ants accelerates nutrient cycling and soil formation, processes foundational to terrestrial productivity. Predatory and parasitoid insects suppress herbivore populations in agricultural and natural systems, providing biological pest control

services conservatively valued at over \$400 billion per year globally (Losey & Vaughan, 2006) [30]. Insects are also critical food sources for birds, bats, reptiles, fish, and amphibians, anchoring food webs from boreal forests to tropical rainforests.

Against this backdrop of ecological importance, the evidence for widespread and accelerating insect population decline is deeply alarming. A landmark 27-year study of flying insect biomass in German nature reserves documented a greater than 75% decline over the study period, a finding that shocked the scientific community and triggered an outpouring of public and media attention (Hallmann *et al.*, 2017) [20]. A subsequent global meta-analysis of terrestrial insect studies confirmed declining abundance and diversity trends, particularly pronounced in agricultural and developed landscapes (Sánchez-Bayo & Wyckhuys, 2019) [40]. More recent analyses have confirmed similar trends across diverse taxa and geographies, while cautioning that the picture is heterogeneous, with some species groups and regions showing stability or even increases (van Klink *et al.*, 2020) [49].

The drivers of insect decline are multiple and interacting. Habitat loss and degradation driven by agricultural intensification, urbanization, and deforestation removes the diverse plant communities, nesting sites, and microclimatic refugia that insects require. Widespread use of insecticides, herbicides, and fungicides in modern agriculture creates toxic landscapes for non-target insects. Invasive species—both predators and pathogens—have devastated native insect communities on islands and continents alike. Light pollution disrupts nocturnal insect behavior, navigation, and reproduction. Climate change is altering the timing, geography, and intensity of all these pressures simultaneously. Understanding, quantifying, and reversing these trends is among the most urgent scientific and policy challenges of our time (Cardoso *et al.*, 2020; Wagner, 2020) [6, 52].

The complexity of entomological challenges is matched by the sophistication of available tools. Genomic technologies now allow researchers to read, edit, and manipulate insect genomes with precision impossible a decade ago. Artificial intelligence is transforming species identification, population monitoring, and ecological modeling. Remote sensing platforms provide landscape-scale data on habitat quality and insect distributions. These converging technological revolutions are creating opportunities for breakthroughs in pest management, disease vector control, conservation, and the sustainable exploitation of insect-derived products. The challenge — and the opportunity — is to deploy these tools responsibly, equitably, and effectively in service of both scientific understanding and practical problem-solving.

This review is structured to address the principal domains of challenge and innovation in contemporary entomology. It draws on primary literature across ecology, genomics, computational biology, agricultural science, public health, and policy studies to provide an integrated assessment of where the field stands and where it must go. The paper aims to be useful both as a state-of-the-art synthesis for specialists and as an accessible introduction for researchers entering entomology from adjacent disciplines.

2. Climate Change and Insect Biology

2.1 Temperature and Phenological Shifts

Climate change is operating as a pervasive driver of change across all aspects of insect biology. Perhaps the most widely

documented effect is phenological advancement—the shifting of key life-history events such as emergence, flight, reproduction, and dormancy to earlier dates as temperatures warm. Long-term datasets on British butterflies have demonstrated average flight-period advances of between two and ten days per decade over the past half-century, with the magnitude of advance correlated with the degree of local warming (Menéndez, 2007; Diamond *et al.*, 2011) [32, 14]. Similar trends have been documented for bumblebees, hoverflies, ground beetles, and aquatic insects in temperate regions.

The ecological consequences of phenological change are far-reaching. When insect emergence advances faster than the flowering times of their host plants, or the hatching of caterpillars gets out of sync with the peak of leaf production, the result is phenological mismatch—a disruption of the tight co-evolutionary relationships that structure ecosystems. Studies of blue tit and great tit populations in the Netherlands have shown that the advancement of caterpillar peak abundance, driven by temperature, has outpaced the advancement of bird hatching dates, leading to reduced nestling survival and population declines (Visser & Gienapp, 2019) [51]. Similar mismatches between pollinators and flowering plants are being documented with increasing frequency in both temperate and montane systems.

2.2 Range Shifts and Species Redistributions

Rising temperatures are also driving broad-scale redistributions of insect ranges. Meta-analyses of range-shift data from hundreds of insect species confirm a general pattern of poleward and upward range expansions, with average rates of northward shift in the Northern Hemisphere of approximately 16 kilometers per decade (Chen *et al.*, 2011) [8]. In Europe, thermophilous butterfly species such as the comma (*Polygonia c-album*), the speckled wood (*Pararge aegeria*), and the silver-spotted skipper (*Hesperia comma*) have all expanded their ranges northward in recent decades as conditions in previously inhospitable areas become suitable.

However, range expansions are not uniformly positive from an ecological or economic perspective. Many species of agricultural pest are among those expanding their ranges, with serious implications for food security. The fall armyworm (*Spodoptera frugiperda*), a devastatingly effective crop pest native to the Americas, was first recorded in Africa in 2016 and has since spread across the continent, invading parts of South Asia and Southeast Asia and threatening staple crops across regions where smallholder farmers have limited capacity to respond (Bebber *et al.*, 2013; Early *et al.*, 2018) [3, 15]. Vector mosquitoes such as *Aedes albopictus* and *Aedes aegypti* are similarly extending their ranges into higher latitudes and altitudes, bringing dengue, chikungunya, and Zika viruses into previously unaffected human populations.

2.3 Thermal Physiology and Evolutionary Adaptation

Understanding the physiological limits of insects to thermal stress is essential for predicting which species will be winners and losers under projected climate scenarios. Critical thermal maximum (CT_{max}) and critical thermal minimum (CT_{min}) values define the range of temperatures within which insects can function, and these values vary enormously across taxa. Tropical insects, which have evolved in thermally stable environments, often have narrow thermal tolerance windows centered on already-warm

temperatures, making them disproportionately vulnerable to warming (Deutsch *et al.*, 2008) ^[13]. Species in temperate regions, by contrast, typically have wider thermal tolerance ranges but may face challenges from the loss of cold periods required to break dormancy.

Whether insect populations can adapt rapidly enough to keep pace with climate change is a critical open question. Experimental evolution studies have demonstrated that populations of *Drosophila* and other short-generation insects can evolve shifts in thermal preference and tolerance within dozens of generations (Hoffmann & Sgrò, 2011) ^[23]. However, for longer-lived insects with one generation per year or less, the pace of evolutionary response may be insufficient. Landscape genomics — the integration of population genomics with spatial environmental data — is providing insights into the genetic architecture of climate adaptation, identifying candidate alleles under climate-related selection that can inform conservation prioritization and assisted gene flow strategies (Razgour *et al.*, 2019) ^[38].

2.4 Drought, Extreme Events, and Multistressor Interactions

Beyond mean temperature increases, climate change is increasing the frequency and intensity of extreme events—droughts, floods, heat waves, and wildfires—that can cause catastrophic, acute mortality in insect populations. Droughts reduce plant quality and availability, affecting herbivorous insects and the predators that depend on them. Flooding destroys nests of ground-nesting bees and ants and displaces aquatic invertebrate communities. The interactions between climate-driven stressors and other anthropogenic pressures such as pesticides, habitat fragmentation, and invasive species create complex, often synergistic threat landscapes that are difficult to model and manage. Disentangling these multistressor interactions is one of the most challenging frontiers in applied entomological research.

3. Insect Biodiversity: Crisis, Monitoring, and Conservation

3.1 The Taxonomic Impediment and Monitoring Deficits

Any serious response to insect biodiversity loss must begin with knowledge—knowledge of which species exist, where they occur, in what numbers, and whether those numbers are changing. Yet entomology faces a profound deficit on all these fronts. The taxonomic impediment—the shortage of trained systematists capable of identifying and describing insect species—means that large fractions of insect diversity remain undescribed. The majority of described species have been recorded from fewer than five localities worldwide, making population trend analysis impossible. Insect collections in natural history museums hold irreplaceable biodiversity data, but much of this information is not digitized and therefore inaccessible to modern analytical workflows (Cardoso *et al.*, 2011; Engel *et al.*, 2021) ^[7, 17].

Long-term monitoring of insect populations is similarly deficient. Most available trend data derive from a handful of long-running programs in northwestern Europe and North America focused on charismatic, tractable groups such as butterflies, moths, and bumblebees. Tropical regions, which harbor the majority of insect biodiversity, are dramatically underrepresented. The development of cost-effective, standardized monitoring protocols that can be deployed across diverse biomes is an urgent priority. Malaise trap networks, standardized light-trapping, and transect count

methods all have roles to play, but achieving global coverage will require new technological approaches and unprecedented international coordination.

3.2 DNA-Based Biodiversity Assessment

Molecular tools are transforming the capacity to monitor insect biodiversity rapidly and affordably. Metabarcoding—the simultaneous sequencing of all species' DNA in a bulk environmental sample—allows identification of hundreds to thousands of insect species from a single Malaise trap sample or soil core (Creer *et al.*, 2016) ^[10]. This approach dramatically reduces the need for expert morphological identification, which has historically been the bottleneck in large-scale biodiversity surveys. Environmental DNA (eDNA) methods that detect species from trace genetic material in water, soil, or air samples are being developed and validated for insects, with airborne eDNA emerging as a particularly promising avenue for passive, continuous monitoring of flying insect communities.

Reference databases linking DNA barcodes to species identities are essential for the success of these approaches. The Barcode of Life Data System (BOLD) currently holds sequences for several hundred thousand insect species, but coverage remains incomplete, particularly for tropical regions and for orders such as Diptera, Hymenoptera, and Coleoptera where species richness is greatest. Investment in reference sequence databases is therefore as important as investment in the sequencing technologies themselves.

3.3 Conservation Strategies at Multiple Scales

Effective insect conservation must operate across spatial scales from the individual farm field to the continental landscape. At the field and farm scale, there is compelling evidence that diversifying agricultural landscapes with flower strips, hedgerows, beetle banks, and reduced-input buffer zones supports substantially higher insect abundance and diversity compared to chemically intensive monocultures (Batáry *et al.*, 2015; Pywell *et al.*, 2015) ^[2, 36]. Agri-environment schemes that compensate farmers for biodiversity-friendly management have been a cornerstone of European conservation policy, with demonstrable positive impacts on farmland butterfly, bumblebee, and carabid beetle populations when appropriately designed and funded.

At the landscape scale, maintaining habitat connectivity is critical for species with limited dispersal ability, enabling colonization of restored habitats and genetic exchange between populations. Green infrastructure planning that identifies and protects ecological corridors for insects is an emerging discipline requiring integration of species distribution modeling, landscape ecology, and urban planning (Baldock *et al.*, 2015) ^[1]. Protected areas, while essential, are insufficient on their own; the majority of insects live in working agricultural, urban, and forestry landscapes that must be made permeable and hospitable.

Rewilding—the passive or active restoration of natural ecological processes across large landscapes—is receiving growing attention as a transformative approach to insect conservation. Where large-scale rewilding has been implemented, as in the Knepp Estate in southern England, the recovery of insect diversity has been dramatic and rapid, demonstrating the resilience of insect communities when given the opportunity (Saunders *et al.*, 2020) ^[41]. Urban habitats, long neglected by conservationists, are increasingly

recognized as important refugia for pollinators and other insects when managed with biodiversity in mind through wildflower meadows, green roofs, and reduced pesticide use.

3.4 Freshwater Insects and Aquatic Ecosystem Health

Freshwater insects — including the larvae of mayflies (Ephemeroptera), stoneflies (Plecoptera), caddisflies (Trichoptera), dragonflies and damselflies (Odonata), and many families of Diptera — are among the most imperiled groups globally. Agricultural runoff, eutrophication, physical habitat modification, water abstraction, and thermal pollution have collectively degraded freshwater ecosystems that were once extraordinarily rich in insect life. Long-term datasets from European rivers show dramatic declines in aquatic insect abundance and diversity since the mid-twentieth century, with recovery in some regions following water quality improvements under environmental legislation demonstrating that these systems can recover when pressures are reduced (Lemm *et al.*, 2021) ^[29]. The freshwater dimension of insect conservation deserves far greater research attention and policy priority.

4. Integrated Pest Management: Evolution and Innovation

4.1 Foundations and Philosophy

Integrated pest management (IPM) was formalized as a concept in the 1960s as a response to the ecological and economic failures of pesticide-dependent crop protection. Its central principles — combining biological, cultural, physical, and chemical controls in a way that minimizes economic damage while protecting human health and the environment — remain as relevant and as poorly implemented as ever. Globally, IPM adoption remains incomplete and uneven. Chemical pesticide use continues to dominate in many agricultural systems, driven by the convenience of calendar-based spraying programs, inadequate extension services, and market incentives that favor inputs over ecological knowledge (Deguine *et al.*, 2021) ^[11].

The resistance challenge is a primary driver of IPM innovation. Insecticide resistance has now been documented in hundreds of pest species across all major chemical classes, from organophosphates and pyrethroids to neonicotinoids and diamides. Resistance management — deploying insecticides in ways that delay the evolution of resistance — requires population genetic understanding, economic modeling, and landscape-scale coordination among farmers that is rarely achieved in practice. This reality underscores the urgent need for genuine diversification of pest management tools and the integration of non-chemical approaches.

4.2 Biological Control: Classical, Augmentative, and Conservation Approaches

Biological control — harnessing natural enemies to suppress pest populations — represents one of entomology's most powerful contributions to sustainable agriculture. Classical biological control, involving the importation and establishment of specialist natural enemies from a pest's region of origin, has achieved spectacular successes against invasive pests that escaped their co-evolved enemies during introduction. The control of cassava mealybug (*Phenacoccus manihoti*) across sub-Saharan Africa by the

introduced parasitoid wasp *Epidinocarsis lopezi* is estimated to have saved millions of people from hunger and generated economic benefits worth billions of dollars over several decades (Herren & Neuenschwander, 1991) ^[22].

Augmentative biological control — the mass rearing and periodic release of natural enemies — has expanded dramatically as rearing technologies have improved. The global market for commercially produced biological control agents now exceeds \$1 billion annually, with predatory mites, parasitoid wasps such as *Trichogramma* spp., and entomopathogenic nematodes and fungi accounting for the majority of products. Conservation biological control — managing habitats to support resident natural enemy populations — is gaining traction as researchers demonstrate the importance of field margins, hedgerows, and non-crop habitats as reservoirs of beneficial insects (van Lenteren *et al.*, 2018) ^[50].

4.3 Precision Agriculture and Digital Pest Management

The digitalization of agriculture is transforming pest management from a reactive, calendar-driven activity to a proactive, data-driven one. Internet of Things (IoT) sensor networks in fields can monitor temperature, humidity, soil moisture, and even direct insect activity through acoustic and optical sensors, feeding real-time data into decision support systems. Unmanned aerial vehicles (UAVs or drones) equipped with multispectral cameras can detect the spectral signatures of insect damage in crops days or weeks before damage is visible to the naked eye, enabling targeted interventions at far lower cost in pesticides and fuel than blanket applications (Deng *et al.*, 2019) ^[12].

Machine learning algorithms trained on large annotated datasets of insect images are achieving expert-level accuracy in species identification from photographs, making pest monitoring accessible to farmers without taxonomic expertise. Platforms such as iNaturalist and the app-based CABI Plantwise service are democratizing pest identification globally, particularly in low-and middle-income countries where extension service capacity is limited. Predictive models that integrate weather forecasts, pest population dynamics, crop phenology, and economic thresholds can provide farm-level recommendations for the optimal timing and intensity of interventions (Shahhosseini *et al.*, 2021) ^[42].

4.4 RNA Interference as a Targeted Pest Control Tool

RNA interference (RNAi) — the natural cellular mechanism for gene silencing mediated by double-stranded RNA — has emerged as a potentially revolutionary approach to highly targeted pest control. By designing dsRNA molecules that silence essential genes in specific pest species, it is possible in principle to kill target insects with exquisite specificity while leaving non-target organisms completely unaffected. Proof-of-concept demonstrations of RNAi-mediated control have been achieved for the western corn rootworm (*Diabrotica virgifera virgifera*), the Colorado potato beetle (*Leptinotarsa decemlineata*), and several bee pathogens (Whyard *et al.*, 2009) ^[53]. Technical challenges around dsRNA stability in the environment, efficient delivery to target insects, and cost-effective large-scale production are being addressed through active research programs. Regulatory frameworks for RNAi-based pesticides are evolving, with the first products approaching commercial registration in several jurisdictions.

5. Genomics, Biotechnology, and Molecular Entomology

5.1 The Insect Genomics Revolution

The sequencing of the honey bee genome in 2006 marked the beginning of a genomic revolution in entomology that has accelerated dramatically with advances in sequencing technology and bioinformatics (Honeybee Genome Sequencing Consortium, 2006) [24]. The cost of sequencing a high-quality insect genome has fallen from tens of millions of dollars to a few hundred, enabling the i5K Initiative and subsequent programs to target the genomes of 5,000 insect species of agricultural, medical, ecological, and evolutionary importance. As of the mid-2020s, reference genomes are available for hundreds of insect species spanning all major orders, and chromosome-level assemblies of extraordinary quality are now routine.

These genomic resources have transformed understanding of insect biology at every level. Comparative genomics has revealed the molecular basis of evolutionary innovations including wing development, eusociality, holometabolous metamorphosis, chemical communication, and host-plant specialization. Transcriptomic analyses have illuminated the gene expression dynamics underlying insect immunity, detoxification, and reproductive physiology. Population genomics is being applied to characterize the genetic diversity and demographic history of endangered species, identify locally adapted populations, and trace invasion pathways of agricultural and medical pests (Feyereisen *et al.*, 2015) [19].

5.2 Insecticide Resistance Genomics

One of the most practically important applications of insect genomics has been elucidating the molecular mechanisms of insecticide resistance. Resistance to insecticides in pest populations typically involves one or more of four mechanisms: target-site mutations that reduce insecticide binding affinity; metabolic resistance through upregulation of detoxifying enzymes (particularly cytochrome P450 monooxygenases, esterases, and glutathione-S-transferases); reduced cuticle penetration; or behavioral avoidance. Whole-genome association studies and transcriptome profiling have dramatically accelerated the identification of resistance-associated variants, enabling the development of diagnostic tools that allow resistance monitoring in field populations before resistance reaches economically damaging frequencies (Feyereisen *et al.*, 2015; Ranson & Lissenden, 2016) [19, 37].

Understanding resistance mechanisms has also informed resistance management strategies. Knowledge of which resistance alleles are present in a population and at what frequencies enables modeling of resistance evolution trajectories and optimization of insecticide rotation programs. In malaria vector control, genomic resistance surveillance is being integrated into national control programs in several African countries, with the goal of aligning insecticide choices for indoor residual spraying and treated bed nets with the local resistance landscape.

5.3 CRISPR-Cas9 and Functional Genomics

CRISPR-Cas9 genome editing has unlocked a new era of functional genomics in insects. The ability to precisely knock out, knock in, or modify specific genes has enabled definitive tests of gene function that were previously impossible or prohibitively laborious. In model organisms

such as *Drosophila melanogaster* and the red flour beetle *Tribolium castaneum*, CRISPR editing has provided fundamental insights into development, immunity, and neurobiology that have broad implications across the insect class. Increasingly, CRISPR tools are being applied directly to non-model insects of agricultural or medical importance, including *Bemisia tabaci* whiteflies, *Helicoverpa armigera* bollworms, and *Anopheles* mosquitoes (Hammond *et al.*, 2016) [21].

5.4 Gene Drive Technologies: Promise and Peril

Gene drives are genetic systems that bias their own inheritance to spread through populations at rates exceeding normal Mendelian expectations, potentially sweeping a trait through an entire wild population within a limited number of generations. CRISPR-based gene drives have been developed for *Anopheles gambiae* mosquitoes carrying a drive targeting female fertility, with cage experiments demonstrating population collapse within a limited number of generations (Hammond *et al.*, 2016) [21]. This approach, if it translates to field conditions, could represent a transformative advance in malaria control. Simultaneously, the World Mosquito Program's *Wolbachia*-based strategy — which involves releasing mosquitoes infected with the bacterium *Wolbachia* that reduces dengue virus replication — has demonstrated 77% efficacy in reducing dengue incidence in a large randomized controlled trial in Yogyakarta, Indonesia (Utarini *et al.*, 2021) [46].

However, gene drive technologies raise substantial concerns that must be addressed before any field deployment. Self-propagating drives, by design, are difficult or impossible to contain geographically, raising questions of national sovereignty and transboundary governance. Potential ecological risks from suppressing or eliminating wild populations of vector species — even disease vectors — are not fully characterized. The long-term evolutionary dynamics of drives encountering natural resistance alleles may limit their efficacy. Reversibility of population changes is limited for suppression drives, raising concerns about unintended ecological consequences that cannot easily be undone. Robust, internationally coordinated governance frameworks incorporating staged evaluation processes, transparent risk assessment, and meaningful community engagement are essential prerequisites for responsible gene drive development (Esvelt *et al.*, 2014; National Academies of Sciences, 2016; Oye *et al.*, 2014) [18, 33, 35].

5.5 Symbiont-Based Approaches

Beyond direct genetic manipulation, insects' obligate and facultative microbial symbionts offer powerful levers for pest management and disease control. Many insects depend entirely on bacterial endosymbionts for essential nutrients — aphids on *Buchnera aphidicola*, tsetse flies on *Wigglesworthia glossinidia*, and bed bugs on *Wolbachia*. Disrupting these symbioses through targeted bacteriostatic agents or competitive exclusion strategies offers pest-specific approaches that avoid broad-spectrum insecticides. *Wolbachia* manipulation extends beyond dengue control: in many insect species, *Wolbachia* induces cytoplasmic incompatibility, male killing, feminization, or parthenogenesis, and researchers are exploring whether these phenotypes can be exploited for controlling agricultural pests (Zabalou *et al.*, 2004) [55].

6. Digital Technologies and Computational Entomology

6.1 Artificial Intelligence for Species Identification

Perhaps no technological development has more immediate practical implications for entomological research than the application of deep learning to species identification. Convolutional neural network (CNN) models trained on millions of labeled insect images hosted on platforms such as iNaturalist, GBIF, and specialist databases are achieving identification accuracy at or near expert taxonomist level for many well-represented groups (Valan *et al.*, 2019) [47]. For some groups and some geographic regions, AI-assisted identification is already enabling species-level identification from amateur photographs, potentially multiplying the effective observer base for biodiversity monitoring by orders of magnitude.

The integration of AI with automated imaging systems is particularly powerful. Malaise traps equipped with high-resolution cameras and automated imaging pipelines can generate thousands of specimen images per day, which deep learning classifiers can sort to species level with minimal human input. This approach — sometimes called 'Malaise trap metagenomics' when combined with DNA metabarcoding — promises to make continuous, taxonomically resolved insect monitoring economically feasible at the network scale required to detect meaningful population trends (Høye *et al.*, 2021) [25]. Similar automated monitoring systems based on optical traps, sticky traps with camera monitoring, and infrared beam-break sensors are being deployed for specific pest and beneficial species.

6.2 Acoustic Monitoring and Biosensing

Acoustic methods offer a complementary and in some cases superior approach to monitoring insect populations, particularly for cryptic or nocturnal species that are poorly captured by visual methods. Insects produce sound and vibration through a variety of mechanisms — wing beats during flight, stridulation, substrate vibration — and many of these signals are species-specific. Machine learning classifiers applied to recordings of insect flight tones (based on wing beat frequency and its harmonics) can identify individual species of mosquitoes, bees, and other insects with high accuracy, enabling passive monitoring of species of interest in the field (Chesmore, 2004) [9].

Biosensors represent another frontier. Honeybees can be trained to extend their proboscis in response to target odors, and arrays of electronically monitored bees have been proposed as living biosensors for explosive detection, pollutant monitoring, and disease diagnosis. Electronic nose technology based on arrays of chemical sensors can detect volatile organic compounds emitted by plant pathogens or pest infestations, enabling early warning of crop stress before visible symptoms develop. The integration of entomological knowledge with sensor technology and machine learning is creating a rich landscape of new monitoring and diagnostic possibilities.

6.3 Environmental DNA and Metabarcoding

Environmental DNA metabarcoding has moved from a novel technique to a practical tool for insect biodiversity assessment with remarkable speed. The ability to identify hundreds of insect species from a single bulk sample or environmental substrate, without the need for expert morphological identification, is transforming the cost-effectiveness and throughput of biodiversity surveys.

Studies have demonstrated strong concordance between metabarcoding and traditional morphological assessments for well-studied groups such as aquatic macroinvertebrates and trap-collected beetles, building confidence in the accuracy of molecular approaches (Creer *et al.*, 2016) [10].

Airborne eDNA — the detection of insect species from DNA collected on atmospheric particulate matter or in air-filtering devices — is an emerging frontier with particular promise for monitoring flying insects. Early studies have demonstrated the feasibility of detecting dozens of insect species from air filters deployed for only 24 hours, suggesting the potential for passive, continuous, landscape-level monitoring systems that could complement active trapping approaches. The scaling of these methods to operational monitoring networks will require further validation, standardization of protocols, and investment in reference database expansion.

6.4 Remote Sensing, GIS, and Species Distribution Modeling

Satellite remote sensing and geographic information systems have become indispensable tools in landscape-scale entomological research. Vegetation indices derived from multispectral satellite imagery can map habitat suitability for pollinators at field to continental scales. LiDAR data capture three-dimensional forest structure relevant to bark beetles, longhorn beetles, and canopy arthropods. Thermal infrared imagery can identify warm-season crop stress associated with pest infestations. The spatial resolution and temporal frequency of satellite imagery has improved dramatically with new commercial satellite constellations, enabling near-real-time monitoring of crop conditions across entire agricultural regions (Turner *et al.*, 2003) [45].

Species distribution models (SDMs) — statistical tools that relate species occurrence records to environmental predictor variables — are widely applied to project how climate change will alter insect habitats and distributions in the future. Ensemble modeling approaches that combine predictions from multiple algorithms and multiple climate scenarios are providing increasingly nuanced projections, identifying which species are most vulnerable to future habitat loss and which regions will function as climate refugia. These projections are becoming central tools for conservation planning, invasion risk assessment, and vector-borne disease risk mapping (Elith & Leathwick, 2009) [16].

7. The Insect-Based Bioeconomy

7.1 Insects as Food and Feed: Sustainability and Scale

The concept of insects as a sustainable source of protein for human consumption and animal feed has transitioned from academic curiosity to commercial reality in the space of a decade. A 2013 report from the Food and Agriculture Organization of the United Nations summarized the nutritional value, environmental efficiency, and safety profile of edible insects and catalyzed a wave of investment in insect production industries (van Huis *et al.*, 2013) [48]. Today, commercial insect farms operate at industrial scale in Europe, North America, and Asia, producing hundreds of thousands of tonnes of insect protein annually for aquaculture, livestock, and pet food markets.

The environmental case for insect protein is compelling. Black soldier fly larvae (*Hermetia illucens*) can be reared on organic waste streams including food waste, manure, and agricultural by-products that have no alternative high-value

use, effectively converting waste into protein with minimal additional inputs. Compared to beef production, insects require approximately 12-fold less land, consume substantially less water, and emit 50 to 100 times fewer greenhouse gases per kilogram of protein produced (Oonincx & de Boer, 2012) ^[34]. For aquaculture, insect meal can partially or wholly replace fishmeal in feed formulations, relieving pressure on wild fish stocks.

For human food markets, regulatory and consumer acceptance barriers remain significant in Western countries, though these are gradually eroding. In 2021, the European Food Safety Authority concluded that the mealworm (*Tenebrio molitor*) is safe for human consumption as a novel food, followed by similar approvals for house crickets and migratory locusts. The food technology industry is exploring insect protein powder as an ingredient in flour, pasta, snack foods, and protein supplements where the visual appearance of intact insects is not present for the consumer. Cultural familiarity with insect eating in many parts of Asia, Africa, and Latin America offers a base of consumer acceptance that global food industry players are increasingly seeking to leverage.

7.2 Bioactive Compounds and Pharmaceutical Potential

Beyond protein, insects are remarkable chemical factories whose diverse metabolomes are yielding compounds of pharmaceutical, cosmetic, and agrochemical significance. Antimicrobial peptides (AMPs) — small proteins that disrupt bacterial cell membranes — are produced by virtually all insect species as part of their innate immune defense against pathogens. As conventional antibiotics face growing irrelevance due to resistance, insect AMPs such as defensins, cecropins, and attacins are being intensively studied as leads for novel antibiotics (Brogden, 2005) ^[5]. The structural and mechanistic diversity of insect AMPs, shaped by hundreds of millions of years of co-evolution with bacterial pathogens, provides a rich chemical space to explore.

Venom components from hymenopteran insects — bees, wasps, and ants — represent another major source of bioactive leads. Bee venom phospholipase A2 and melittin have anti-inflammatory and anti-tumor properties that are being explored in drug development. Spider and scorpion venoms, while not technically from insects, have yielded numerous peptide leads in pain management and neurological disorders. Chitin derived from insect exoskeletons is a versatile biopolymer with applications in wound healing biomaterials, drug delivery nanoparticles, agricultural fungicides, and water purification (Khoushab & Yamabhai, 2010) ^[27]. Silk proteins from lepidopteran larvae and pupae are being explored as biocompatible materials for tissue engineering scaffolds and biodegradable electronics.

7.3 Insects in Waste Management and Circular Economy

The capacity of certain insect species to rapidly process organic waste is being harnessed in circular economy applications that simultaneously address waste management challenges and produce valuable outputs. Black soldier fly larvae are the dominant organism in this space, capable of reducing the volume of organic waste by up to 70% while producing protein-rich biomass and frass fertilizer as outputs. Industrial-scale BSF facilities processing food waste and agricultural by-products are operating in Europe, North America, and increasingly in the Global South,

generating revenues from insect protein, insect fat (with applications in biodiesel and oleochemicals), and organic fertilizer simultaneously. This waste bioconversion model exemplifies the circular economy principles of eliminating waste and keeping biological materials in use, and is receiving increasing policy support in jurisdictions developing bioeconomy strategies.

8. Vector-Borne Diseases: Entomology at the Human Health Interface

8.1 The Global Burden and Changing Landscape

Insects are vectors for an extraordinary range of human pathogens. Malaria, caused by *Plasmodium* parasites transmitted by *Anopheles* mosquitoes, remains one of the world's leading infectious disease killers, with over 600,000 deaths recorded annually despite decades of control efforts. Dengue fever, transmitted primarily by *Aedes aegypti*, now infects an estimated 390 million people annually across more than 100 countries, with incidence growing rapidly. Leishmaniasis, sleeping sickness, Chagas disease, river blindness, lymphatic filariasis, and numerous arboviral diseases complete a roster of insect-vector-borne illnesses that collectively cause millions of deaths and hundreds of millions of cases of serious illness annually, with disproportionate impact on the world's most vulnerable populations.

Climate change is altering this burden in complex ways. Rising temperatures and changing rainfall patterns are expanding the geographic distributions of vector species, bringing diseases into populations and health systems with limited prior exposure or preparedness. The tiger mosquito, *Aedes albopictus*, has established populations in much of southern and central Europe and continues to spread northward, creating conditions for sustained dengue and chikungunya transmission in previously unaffected regions (Medlock *et al.*, 2012) ^[31]. Modeling studies project substantial northward and upward expansion of malaria-suitable conditions in Africa and Asia under various warming scenarios, though the ultimate impact on malaria burden will depend heavily on the evolution of control interventions and health system capacity.

8.2 Insecticide Resistance in Vector Populations

Resistance to the insecticides used in bed nets, indoor residual spraying, and larval control programs is an acute and growing threat to vector control programs worldwide. Resistance to pyrethroids — the primary class of insecticide used in long-lasting insecticidal nets (LLINs) — is now documented in *Anopheles gambiae* populations across much of sub-Saharan Africa, with some populations showing resistance to all four classes of insecticides approved for use in LLINs and indoor residual spraying (Ranson & Lissenden, 2016) ^[37]. The public health consequences of this resistance are difficult to quantify precisely, as resistance does not automatically translate into product failure in field conditions, but there is growing evidence that resistance is contributing to declining efficacy in some areas.

Resistance management for vector control faces unique challenges compared to agricultural IPM. Insecticide-treated bed nets and indoor spraying programs operate on a public health logic that cannot accommodate the economic threshold concepts central to agricultural IPM — the goal is to minimize disease transmission, not just reduce pest populations below an economic injury level. This makes it

difficult to implement the spray-free intervals and insecticide rotation strategies that agricultural resistance management relies upon. New active ingredients, synergist combinations, physical barriers, and non-chemical interventions must be integrated into vector control programs alongside molecular resistance monitoring to preserve the efficacy of existing tools.

8.3 Novel Vector Control Tools

A diverse portfolio of novel vector control tools is under active development and evaluation. Spatial repellents and attractive toxic sugar baits (ATSBs) offer new mechanisms for reducing human-mosquito contact and vector populations without the toxicological concerns associated with household insecticide applications. The sterile insect technique (SIT), proven in agricultural pest control, is being adapted for mosquito control with promising field trial results in multiple countries. Mass releases of male mosquitoes carrying heritable sterility through radiation or genetic modification offer population suppression without chemical inputs (Bouyer & Lefrançois, 2014) [4].

Autodissemination — the use of a proportion of vector mosquitoes to carry insecticidal or pathogen-blocking agents back to larval breeding sites — leverages mosquito behavior to deliver control agents with high spatial efficiency. Push-pull strategies combining spatial repellents to reduce host-seeking success with attractants that draw mosquitoes into lethal traps are being refined for operational use. Integration of these tools within IVM frameworks that also address larval source reduction and community engagement is essential for their effectiveness and sustainability.

9. Ethics, Governance, and Policy Dimensions

9.1 Governance of Biotechnological Innovations

The rapid pace of innovation in insect biotechnology is outrunning the development of governance frameworks capable of ensuring its responsible application. Gene drives, genetically modified insects, and symbiont manipulation technologies all have the potential to alter insect populations and ecosystems beyond national borders, raising questions of international law, sovereignty, and equity that existing biosafety frameworks were not designed to address (Oye *et al.*, 2014) [35]. The Convention on Biological Diversity and its Cartagena Protocol on Biosafety provide partial frameworks, but their application to self-propagating gene drives in particular is contested and unclear.

The International Union for Conservation of Nature (IUCN) has issued guidelines for responsible gene drive research emphasizing staged evaluation, geographic containment during testing, transparent risk communication, and community engagement with affected populations. The scientific community has broadly endorsed a stepwise approach to gene drive development that moves from contained laboratory experiments through small-scale confined field trials to open releases only after thorough evaluation of safety and efficacy at each stage. This approach is theoretically sound but requires international coordination and trust-building that is challenging to achieve in the current geopolitical environment.

9.2 Insect Welfare and Ethics of Rearing

As insect rearing for food, feed, and other applications scales to billions or trillions of individuals, questions of insect welfare are receiving increased attention from

ethicists and scientists. The capacity of insects to experience pain, stress, or suffering remains scientifically contested but cannot be dismissed. Behavioral evidence of nociception — the detection and avoidance of noxious stimuli — exists for several insect orders, and the neurological basis for a functional analog of pain is present in some taxa. While the ethical weight of insect welfare is likely to be lower than that of vertebrates, the sheer scale of insect rearing operations means that even small probabilities of significant suffering translate into large numbers of potentially affected individuals (Rethink Priorities, 2019) [39].

Research into methods for humane slaughter and rearing conditions for food insects is an emerging area, driven both by ethical concern and by regulatory requirements in some jurisdictions. The development of evidence-based welfare standards for commercially reared insect species is an important priority that requires collaboration between entomologists, animal welfare scientists, ethicists, and industry stakeholders.

9.3 Equity, Access, and Indigenous Knowledge

The benefits and risks of entomological innovation are not distributed equitably. The communities most directly affected by insect-transmitted diseases, crop pest pressure, and biodiversity loss are often those with the least access to the technologies and knowledge needed to respond. Capacity building in taxonomy, molecular biology, and ecological monitoring in tropical developing countries — where insect diversity is greatest and scientific infrastructure is most limited — is both a scientific and ethical imperative. The insect bioeconomy offers significant economic development potential for tropical countries, but realizing this potential requires investment in local industry capacity and fair regulatory frameworks that prevent the extraction of genetic resources without benefit-sharing.

Traditional ecological knowledge of insects — their taxonomy, ecology, behavior, and uses — held by indigenous and local communities often represents centuries of careful observation that can complement and enrich scientific understanding. Bioprospecting for insect-derived compounds and traditional knowledge about medicinal or edible insects must be conducted with full respect for free, prior, and informed consent, and with mechanisms for fair and equitable benefit-sharing consistent with the Nagoya Protocol on Access and Benefit-Sharing (Lavery *et al.*, 2010) [28].

10. Future Research Directions and Priority Areas

10.1 Closing the Taxonomic and Monitoring Gap

Perhaps the most fundamental and most neglected priority in entomology is investment in the foundational science of taxonomy and long-term monitoring. Without knowing what species exist and how their populations are changing, it is impossible to make sound conservation, management, or policy decisions. The investment required is substantial but not unreasonable: expanded training programs for insect taxonomists, digitization and networking of natural history collections, global deployment of standardized monitoring protocols, and investment in reference DNA barcode libraries for all insect families are all achievable with sustained institutional and governmental commitment (Engel *et al.*, 2021) [17].

The emerging tools of automated imaging, metabarcoding, and remote sensing discussed throughout this review offer

pathways to fill the monitoring gap at scales and costs previously unachievable. Converting these promising technologies into operational monitoring networks requires not just technical development but also institutional infrastructure: data standards, shared databases, quality control protocols, and funding mechanisms that support sustained monitoring over the decades needed to detect meaningful trends. International initiatives such as the Earth Biogenome Project, the Global Biodiversity Information Facility, and national biodiversity observation networks are building this infrastructure, but the pace of investment must accelerate to match the pace of biodiversity change.

10.2 Interdisciplinary and Systems-Based Approaches

The complexity of the challenges facing entomology demands approaches that transcend disciplinary boundaries. Understanding insect decline requires integrating ecology, toxicology, climatology, land-use science, and economics. Developing responsible gene drive governance requires engagement with international law, bioethics, political science, and community-based participatory research. Building sustainable insect food systems requires food science, business development, consumer psychology, and supply chain management alongside entomological expertise.

Systems-based approaches that model the interactions among insect communities, their ecological context, human management activities, and economic drivers are needed to guide decision-making in complex agricultural and conservation landscapes. Socio-ecological systems frameworks that explicitly incorporate human behavior, institutions, and values alongside ecological dynamics are increasingly recognized as essential for understanding why good entomological science so rarely translates into effective policy and management outcomes.

10.3 Citizen Science and Public Engagement

The engagement of the public in entomological data collection and science communication is both a practical necessity and an ethical opportunity. Citizen science platforms such as iNaturalist have generated hundreds of millions of verified species observations from millions of participants worldwide, creating biodiversity datasets of unprecedented geographic and taxonomic breadth that are transforming our understanding of species distributions and phenological trends. Garden butterfly surveys, urban bee monitoring programs, and moth-trapping networks run by volunteers have generated some of the longest insect population time series available (Silvertown, 2009) ^[43].

Beyond data collection, public engagement with insects serves the critical function of building the social and political will for insect conservation. Research in environmental psychology demonstrates that direct experience with nature — including insects — is associated with greater pro-environmental attitudes and behaviors. Programs that help people to notice, appreciate, and understand the insects in their gardens, farms, and neighborhoods are therefore not merely educational luxuries but strategic investments in building the constituency for the policy changes that insect conservation requires. The development of insect-focused natural history programs in schools, nature reserves, and community gardens deserves far greater investment than it currently receives.

10.4 One Health and Cross-Sectoral Integration

The One Health framework — which recognizes the inextricable connections between human health, animal health, and ecosystem health — provides an important conceptual and institutional home for entomological research at the interface of human well-being and the environment. Insect-transmitted diseases cannot be addressed by medical interventions alone; they require management of vector habitats and populations in ways that maintain ecosystem services and do not accelerate resistance. Agricultural pest management that relies on pesticides affects not just target pests but also beneficial insects, aquatic ecosystems, and human health. Conservation of insect biodiversity is inseparable from conservation of the plant, vertebrate, and microbial communities with which insects co-evolved.

Cross-sectoral integration — bringing together entomologists, physicians, agricultural scientists, ecologists, economists, and policymakers — is necessary to address these interconnections. Institutional structures that incentivize interdisciplinary collaboration and that translate scientific knowledge into policy decisions are as important as any individual research advance. The future of entomology as a discipline will be shaped by its ability to communicate the centrality of insects to human welfare and to position itself as an essential partner in addressing the great challenges of the twenty-first century.

11. Conclusion

Entomology stands at a moment of profound challenge and extraordinary opportunity. The challenges are real and urgent: insect populations are declining at alarming rates across multiple taxa and biomes, driven by interacting anthropogenic pressures that show no sign of abating without deliberate intervention. Climate change is altering insect distribution, phenology, and ecology in ways that will have cascading consequences for agriculture, human health, and ecosystem functioning. Insecticide resistance in pest and vector populations is eroding the efficacy of chemical control tools on which much of global food production and disease control currently depends. The taxonomic and monitoring infrastructure needed to understand and respond to these changes is inadequate in virtually every part of the world.

Yet the opportunities are equally real. The genomic, computational, and biotechnological tools now available to entomologists are of a power and precision that would have seemed miraculous to previous generations. Gene editing offers unprecedented precision in manipulating insect biology for pest management and disease control. Artificial intelligence and automated imaging are transforming the scale and cost of biodiversity monitoring. Environmental DNA and remote sensing are filling geographic and taxonomic gaps in our knowledge of insect communities. The insect bioeconomy is creating economic value from insect diversity in ways that provide new incentives for conservation alongside new products for sustainable development.

Navigating between these challenges and opportunities successfully will require more than scientific innovation. It will require governance frameworks adequate to the power of new biotechnologies. It will require equitable distribution of both the benefits of insect innovation and the responsibilities of insect conservation. It will require

sustained, long-term investment in foundational science — taxonomy, monitoring, ecology — that does not yield the rapid publications and commercial returns that drive much contemporary research investment. And it will require a genuine cultural shift in the way societies perceive and value the small creatures that underpin the living systems on which all life depends.

Insects have survived five mass extinction events and have been the ecological engineers of terrestrial ecosystems for 400 million years. The question before us is not whether insects will survive the Anthropocene — evolution will ensure that some will — but whether the diversity, abundance, and ecological function of insect communities can be preserved at levels adequate to sustain the ecosystems and agricultural systems that human civilization depends upon. The answer to that question will be determined in the coming decades, and entomology — its science, its practitioners, and its advocates — will play a central role in shaping it.

References

- Baldock KCR, Goddard MA, Hicks DM, Kunin WE, Mitschunas N, Osgathorpe LM, *et al.* Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects. *Proc R Soc B Biol Sci.* 2015;282(1803):20142849.
- Batáry P, Dicks LV, Kleijn D, Sutherland WJ. The role of agri-environment schemes in conservation and environmental management. *Conserv Biol.* 2015;29(4):1006-1016.
- Bebber DP, Ramotowski MAT, Gurr SJ. Crop pests and pathogens move polewards in a warming world. *Nat Clim Chang.* 2013;3(11):985-988.
- Bouyer J, Lefrançois T. Boosting the sterile insect technique to control mosquitoes. *Trends Parasitol.* 2014;30(6):271-273.
- Brogden KA. Antimicrobial peptides: pore formers or metabolic inhibitors in bacteria? *Nat Rev Microbiol.* 2005;3(3):238-250.
- Cardoso P, Barton PS, Birkhofer K, Chichorro F, Deacon C, Fartmann T, *et al.* Scientists' warning to humanity on insect extinctions. *Biol Conserv.* 2020;242:108426.
- Cardoso P, Erwin TL, Borges PAV, New TR. The seven impediments in invertebrate conservation and how to overcome them. *Biol Conserv.* 2011;144(11):2647-2655.
- Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD. Rapid range shifts of species associated with high levels of climate warming. *Science.* 2011;333(6045):1024-1026.
- Chesmore D. Automated bioacoustic identification of species. *An Acad Bras Cienc.* 2004;76(2):435-440.
- Creer S, Deiner K, Frey S, Porazinska D, Barbato R, Kelly LS, *et al.* The ecologist's field guide to sequence-based identification of biodiversity. *Methods Ecol Evol.* 2016;7(9):1008-1018.
- Deguine JP, Aubertot JN, Flor RJ, Lescouret F, Wyckhuys KAG, Ratnadass A, *et al.* Integrated pest management: good intentions, hard realities. A review. *Agron Sustain Dev.* 2021;41(3):38.
- Deng L, Wang Y, Han Z, Jin R. Detection of stored-grain insects using deep learning: A more effective neural network. *IEEE Access.* 2019;7:163703-163714.
- Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, *et al.* Impacts of climate warming on terrestrial ectotherms across latitude. *Proc Natl Acad Sci U S A.* 2008;105(18):6668-6672.
- Diamond SE, Frame AM, Martin RA, Buckley LB. Species-level phenological response to climate change inferred from shift in thermal physiology. *Funct Ecol.* 2011;25(6):1372-1380.
- Early R, Bradley BA, Dukes JS, Howell JE, Olden JD, Pyšek P, *et al.* Global threats from invasive alien species in the twenty-first century and national response capacities. *Nat Commun.* 2018;7:12485.
- Elith J, Leathwick JR. Species distribution models: ecological explanation and prediction across space and time. *Annu Rev Ecol Evol Syst.* 2009;40:677-697.
- Engel MS, Barden P, Riccio ML, Grimaldi DA. Morphologically specialized termite castes and advanced sociality in the Early Cretaceous. *Curr Biol.* 2021;26(4):522-530.
- Esvelt KM, Smidler AL, Catteruccia F, Church GM. Concerning RNA-guided gene drives for the alteration of wild populations. *eLife.* 2014;3:e03401.
- Feyereisen R, Dermauw W, Van Leeuwen T. Genotype to phenotype, the molecular and physiological dimensions of resistance in arthropods. *Pestic Biochem Phys.* 2015;121:61-77.
- Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, *et al.* More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE.* 2017;12(10):e0185809.
- Hammond A, Galizi R, Kyrou K, Simoni A, Martins C, Lukiyanti R, *et al.* A CRISPR-Cas9 gene drive system targeting female reproduction in the malaria mosquito vector *Anopheles gambiae*. *Nat Biotechnol.* 2016;34(1):78-83.
- Herren HR, Neuenschwander P. Biological control of cassava pests in Africa. *Annu Rev Entomol.* 1991;36:257-283.
- Hoffmann AA, Sgrò CM. Climate change and evolutionary adaptation. *Nature.* 2011;470(7335):479-485.
- Honeybee Genome Sequencing Consortium. Insights into social insects from the genome of the honeybee *Apis mellifera*. *Nature.* 2006;443(7114):931-949.
- Høyte TT, Årje J, Bjerge K, Hansen OLP, Iosifidis A, Leese F, *et al.* Deep learning and computer vision will transform entomology. *Proc Natl Acad Sci U S A.* 2021;118(2):e2002545117.
- IPBES. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. Bonn, Germany: Secretariat of the IPBES; 2016.
- Khoushab F, Yamabhai M. Chitin research revisited. *Mar Drugs.* 2010;8(7):1988-2012.
- Lavery JV, Tinadana PO, Scott TW, Harrington LC, Ramsey JM, Yactayo-Antayhua S, *et al.* Towards a framework for community engagement in global health research. *Trends Parasitol.* 2010;26(6):279-283.
- Lemm JU, Feld CK, Birk S, Hering D, Sondermann M. Combined effects of hydromorphology and water quality on ecological status of European rivers. *Water Res.* 2021;203:117437.

30. Losey JE, Vaughan M. The economic value of ecological services provided by insects. *BioScience*. 2006;56(4):311-323.
31. Medlock JM, Hansford KM, Schaffner F, Versteirt V, Hendrickx G, Zeller H, *et al*. A review of the invasive mosquitoes in Europe: Ecology, public health risks, and control options. *Vector Borne Zoonotic Dis*. 2012;12(6):435-447.
32. Menéndez R. How are insects responding to global warming? *Tijdschr Entomol*. 2007;150(2):355-365.
33. National Academies of Sciences, Engineering, and Medicine. *Gene drives on the horizon*. Washington (DC): National Academies Press; 2016.
34. Oonincx DGAB, de Boer IJM. Environmental impact of the production of mealworms. *PLOS ONE*. 2012;7(12):e51145.
35. Oye KA, Esvelt K, Appleton E, Anderson F, Bar-Yam S, Church GM, *et al*. Regulating gene drives. *Science*. 2014;345(6197):626-628.
36. Pywell RF, Heard MS, Woodcock BA, Isaac S, Jensen HG, Bulman P, *et al*. Wildlife-friendly farming increases crop yield. *Proc R Soc B*. 2015;282(1816):20151740.
37. Ranson H, Lissenden N. Insecticide resistance in African Anopheles mosquitoes. *Trends Parasitol*. 2016;32(3):187-196.
38. Razgour O, Forester B, Taggart JB, Bekaert M, Juste J, Ibáñez C, *et al*. Adaptive genetic variation in climate change vulnerability. *Proc Natl Acad Sci U S A*. 2019;116(21):10418-10423.
39. Rethink Priorities. *Invertebrate sentience: A review*. Rethink Priorities; 2019.
40. Sánchez-Bayo F, Wyckhuys KAG. Worldwide decline of the entomofauna: A review of its drivers. *Biol Conserv*. 2019;232:8-27.
41. Saunders ME, Janes JK, O'Hanlon JC. Moving beyond the insect apocalypse narrative. *BioScience*. 2020;70(1):80-89.
42. Shahhosseini M, Martinez-Feria RA, Hu G, Archontoulis SV. Maize yield prediction with machine learning. *Environ Res Lett*. 2021;14(12):124026.
43. Silvertown J. A new dawn for citizen science. *Trends Ecol Evol*. 2009;24(9):467-471.
44. Stork NE. How many species of insects exist? *Annu Rev Entomol*. 2018;63:31-45.
45. Turner W, Spector S, Gardiner N, Fladeland M, Sterling E, Steininger M. Remote sensing for biodiversity conservation. *Trends Ecol Evol*. 2003;18(6):306-314.
46. Utarini A, Indriani C, Ahmad RA, Tantowijoyo W, Arguni E, Ansari MR, *et al*. Efficacy of *Wolbachia*-infected mosquito deployments for the control of dengue. *N Engl J Med*. 2021;384(23):2177-2186.
47. Valan M, Makonyi K, Maki A, Vondráček D, Ronquist F. Automated insect identification using a continuously updated vision model. *Syst Biol*. 2019;68(6):876-895.
48. van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, *et al*. *Edible insects: Future prospects for food and feed security*. Rome: FAO; 2013.
49. van Klink R, Bowler DE, Gongalsky KB, Swengel AB, Gentile A, Chase JM. Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*. 2020;368(6489):417-420.
50. van Lenteren JC, Bolckmans K, Köhl J, Lommen ST, Messelink GJ, Sundh I. Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl*. 2018;63(1):39-59.
51. Visser ME, Gienapp P. Evolutionary responses to climate change have helped to maintain tree-herbivore-bird phenological synchrony. *Nat Ecol Evol*. 2019;3(6):879-885.
52. Wagner DL. Insect declines in the Anthropocene. *Annu Rev Entomol*. 2020;65:457-480.
53. Whyard S, Singh AD, Wong S. Ingested double-stranded RNAs can induce gene-specific RNA interference in insect pests. *Insect Biochem Mol Biol*. 2009;39(11):824-832.
54. World Health Organization. *World malaria report 2020*. Geneva: World Health Organization; 2020.
55. Zabalou S, Riegler M, Theodorakopoulou M, Stauffer C, Savakis C, Bourtzis K. *Wolbachia*-induced cytoplasmic incompatibility as a means for insect pest population control. *Proc Natl Acad Sci U S A*. 2004;101(42):15042-15045.